HIGH POWER OPENING SWITCH OPERATION ON HAWK

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Abstract

The Hawk pulsed power generator is used in plasma opening switch (POS) experiments in the 1-μs conduction time regime to study long conduction time switch physics. Experiments reported here include modifying the POS electrode geometry, injecting plasma into the e-beam diode, using gas gun plasma sources (with H_2, He, and Ar gases), and using a helical cathode center conductor in the switch region to increase the total insulating magnetic field. Tapering the cathode center conductor over the 8 cm POS length from 10 cm to, typically, a 2.5 cm diam produced peak load powers of 0.7 TW with 55 kJ delivered to the diode--20% energy efficiency--with carbon-coated flashboards as the plasma source. Performance (voltage, power generated) with a straight 10 cm diam cathode deteriorated when the POS anode outer conductor just downstream of the switch was extended toward the load at the same radius as the switch. Load power was up to 70% higher with a plasma-filled diode (PFD) used in conjunction with the POS for short POS conduction times (400 ns and less). Use of a helical center conductor resulted in dramatically degraded switch performance for >350 ns conduction times. Switch performance with gas guns was generally comparable to that with flashboards in a given switch/load configuration and was independent of the gas (H_2, He, and Ar) used.

Introduction

The Hawk generator[1] is a 600 nH, 1-μF Marx bank that stores 225 kJ at 80-kV charge to deliver up to 720 kA in 1.2 μs to a plasma opening switch (POS). Past experiments and analyses[2] have identified hydrodynamic plasma distortion as the dominant mechanism that controls much of the POS operation.[3] A high density plasma is used to conduct the current pulse, while the opening phase is characterized by a rarefied plasma resulting from redistribution during the conduction phase. The maximum load power is determined by an effective gap for magnetic insulation in the POS. This earlier data indicated that above a critical load impedance the effective gap in the POS, as determined from magnetic insulation arguments, is limited to 3 mm. Above this critical impedance, called the switch-limited regime, current is shunted into the transition section between the switch and the load with the voltage remaining constant. At impedances lower than the critical value, the voltage decreases in proportion to the load impedance, the so called load-limited regime. Maximum load power is obtained at this critical impedance. Increasing the cathode magnetic field (I / r)--by conducting more current (I) or decreasing the cathode radius (r)--allows the fixed-gap POS to remain insulated at a higher voltage. In this way, load voltages up to 2 MV were achieved with a 2.5 cm diam cathode, a factor of 2.8 higher than the Marx voltage.

In this paper, recent Hawk experiments with further modifications to the POS electrode geometry, plasma-filled diodes (PFD), and gas gun plasma sources are discussed.

Tapered Cathodes

Tapered cathodes were employed in the switch region and upstream and downstream of the switch. The larger cathode magnetic

field in tapered regions may insulate the electron flow better and allow higher load powers. Only tapering in the switch region had an effect on performance with significant improvement observed with a taper like that shown in Fig. 1. This gradual 10 to 2.5 cm diam taper through the 8 cm length switch produced load powers up to 0.7 TW (1.5 MV and 465 kA, see Fig. 2) and 55 kJ--20% energy efficiency from the energy stored in the Marx--delivered to the load. Such a taper generated voltages close to those possible with a 2.5 cm diam cathode but with the longer conduction/higher currents associated with a 10 cm diam cathode, producing the high load powers. The importance of geometry on switch performance is illustrated by the fact that when the tapering starts just a few cm further downstream, near the middle of the switch instead of at the upstream end, performance becomes identical to a straight 10 cm diam cathode, i.e. 850 kV and 0.4 TW load power at 900 ns conduction.
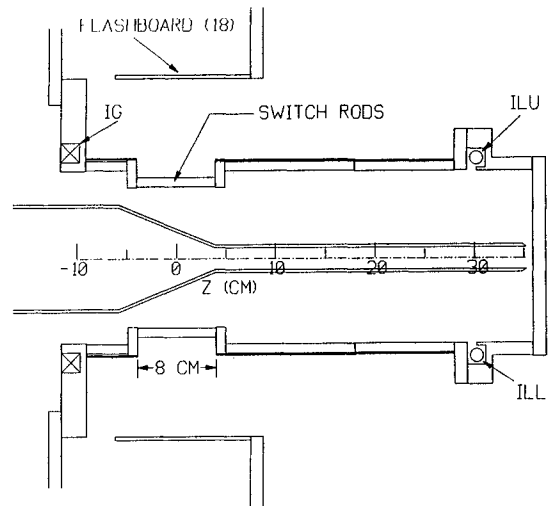

Fig. 1. Hawk front end vacuum section with a 10 cm to 2.5 cm diam cathode taper in the switch region.
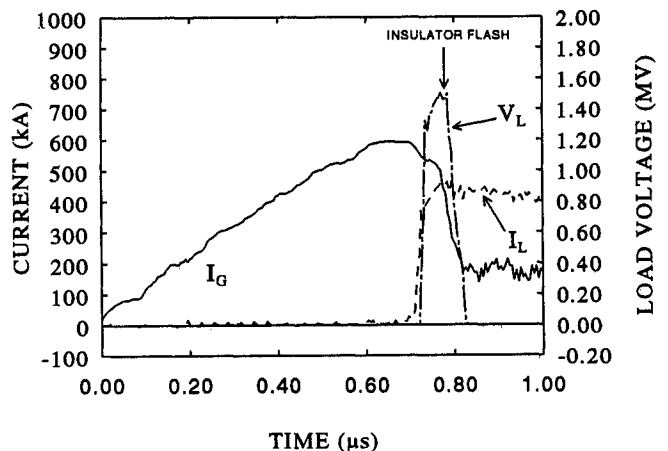

Fig. 2. Generator and load currents and load voltage for the tapered cathode in fig.1. Peak load power is 0.7 TW.

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14. ABSTRACT
The Hawk pulsed power generator is used in plasma opening switch (POS) experiments in the 1-J.lS conduction time regime to study long conduction time switch physics. Experiments reported here include modifying the POS electrode geometry, injecting plasma into thee-beam diode, using gas gun plasma sources (with H2, He, and Ar gases), and using a helical cathode center conductor in the switch region to increase the total insulating magnetic field. Tapering the cathode center conductor over the 8 em POS length from 10 em to, typically, a 2.5 em diam produced peak load powers of0.7 TW with 55 kJ delivered to the diode--20% energy efficiency--with carboncoated flashboards as the plasma source. Performance (voltage, power generated) with a straight 10 em diam cathode deteriorated when the POS anode outer conductor just downstream of the switch was extended toward the load at the same radius as the switch. Load power was up to 70% higher with a plasma-filled diode (PFD) used in conjunction with the POS for short POS conduction times {400 ns and less}. Use of a helical center conductor resulted in dramatically degraded switch performance for >350 ns conduction times. Switch performance with gas guns was generally comparable to that with flashboards in a given switch/load configuration and was independent of the gas (H2, He, and Ar) used.

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Figure 3 shows the peak switch voltage as a function of load impedance at peak power for shots with the taper depicted in Fig. 1. Above ~4 Ω the voltage is roughly constant for a given conduction current--the switch-limited regime. Voltage increases with conduction current and is over 1.6 MV on the longest conduction (600 to 700 kA) switch-limited shots. The 4 Ω impedance is the critical impedance for this geometry, producing 0.7 TW on 600-700 kA conduction shots.

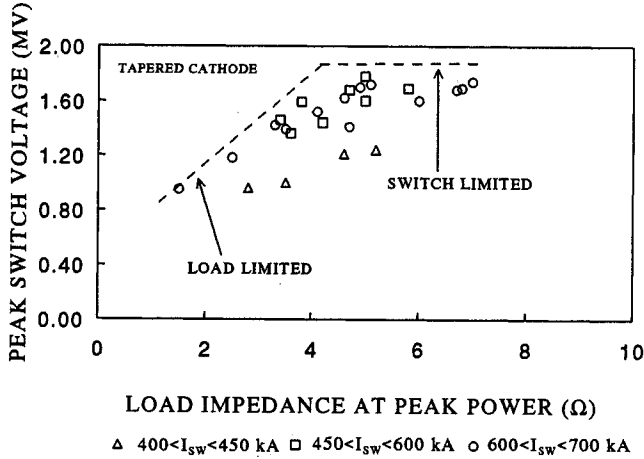A 400<I_{sw}<450 kA   □ 450<I_{sw}<600 kA   o 600<I_{sw}<700 kA

Fig. 3. Peak voltage as a function of load impedance at peak power with the tapered cathode.

The influence geometry can have on switch operation is further illustrated in Fig. 4 where two tapered cathode shots with the same conduction time (same plasma conditions) are shown. In one case, the setup is with the standard 26 cm switch-to-load length in load-limited operation--good current transfer, relatively low voltage--because sufficient switch plasma is accelerated to the load by JxB forces during conduction with this small radius cathode to limit the load impedance at peak power. On the other shot (with the same diode gap) the transition section was extended to 40 cm, allowing high load impedance--switch-limited--operation with higher voltage but lower load current.
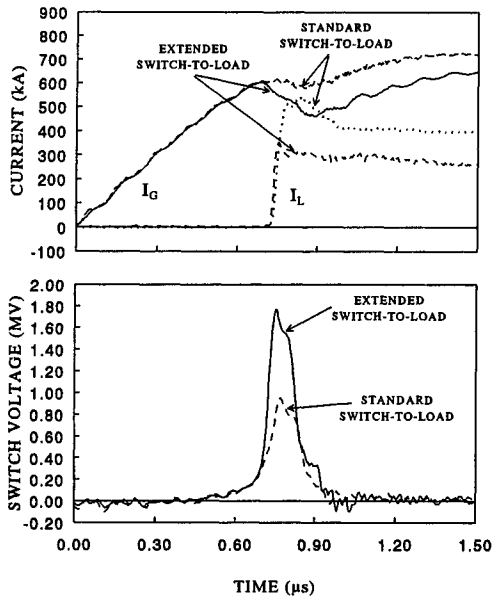

Fig. 4. Two shots with the tapered cathode and the same conduction time and diode gap, but with different switch-to-load lengths.

Anode Modifications

Changes to the anode structure can have a substantial effect on switch opening. One modification was to add a 6 cm long extension to the anode just downstream of the switch at the same radius as the switch rods, providing a 2 cm radial gap in this region with a 10 cm diam cathode. The usual configuration is to expand out to a 4 cm radial gap immediately downstream of the switch rods.

Figure 5 shows data from shots with 6 cm, 2 cm, and no extension for the same 950 ns conduction time. Switch opening with the 6 cm extension is very poor. Most of the current is lost over the last 3 cm length of the extension, with the location where the anode damage begins corresponding to the downstream edge of the switch at opening if the switch translates about half the switch length during the conduction phase. Opening actually improved somewhat as the plasma delay was shortened--an atypical result. A 2 cm extension resulted in better switch opening than the 6 cm extension (for the same conduction time) but still not as good as the no extension standard setup, where current transfer efficiency is 80% and voltages of 800 kV are produced for 950 ns conduction, performance typical of a 10 cm diam cathode.
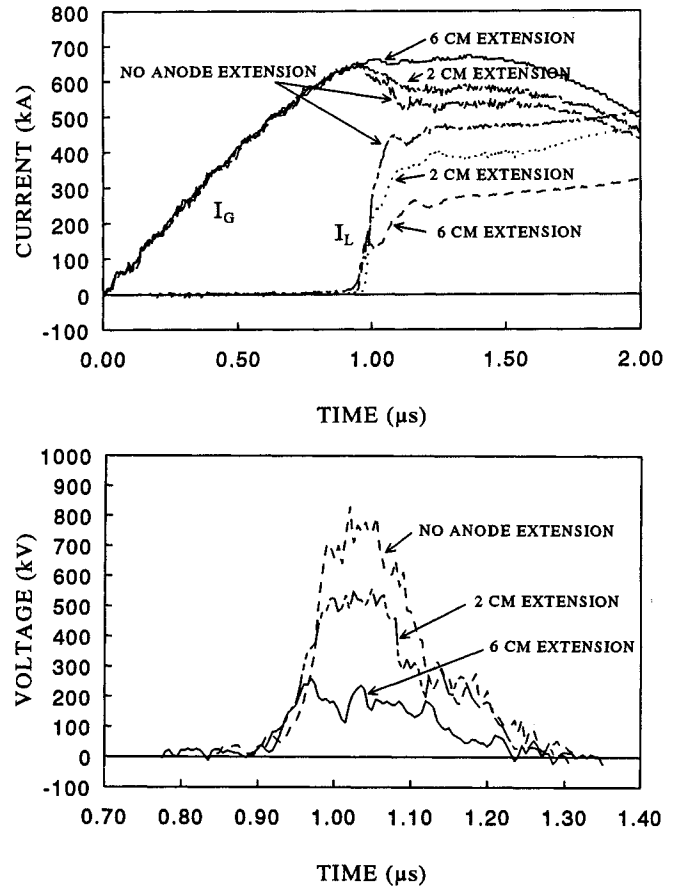

Fig. 5. Changes to the anode geometry can have a substantial effect on switch performance: an extension added to the anode just downstream of the switch but at the same radius as the switch rods degrades switch opening. The cathode is 10 cm in diameter.

Plasma-Filled Diodes

PFD experiments were done by injecting plasma from a flashboard downstream of the diode into the diode gap through holes in the anode strike plate. The PFD was used in three cathode configurations : a straight 5 cm diam cathode, a 10 to 5 cm diam switch taper, and a

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tapered cathode which was flared out to a 10 cm diam at the diode as shown in Fig. 6. Flaring the cathode at the diode was a convenient way of reducing the load impedance at peak power for a given diode gap, operating closer to the critical impedance. On long POS conduction time shots, peak load power was up to 30% higher with the PFD. However, some switch plasma reached the load on these long conduction shots--the impedance rises from zero even with no independent PFD plasma--so there are no true vacuum diode shots for comparison.
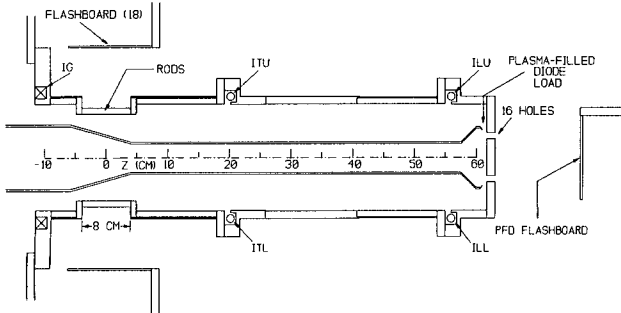

Fig. 6. One of the (cathode) configurations used with a plasma-filled diode load.

For short POS conduction times, where switch plasma does not reach the load and the load with no PFD behaves as a vacuum diode, the enhancement in load power using the PFD was greater. Figure 7 shows peak load power on shots with 400 ns POS conduction times was up to 70% higher with the PFD (for similar load impedance at peak power). With the PFD, somewhat higher voltage is produced (indicating a larger switch gap) and more current reaches the load. This is consistent with the reduced vacuum electron flow with a PFD load that is seen in simulations. Also, the PFD shots showed strong on-axis beam pinching in the diode, evident from x-ray pinhole pictures and damage on the anode plate. This is probably because the plasma is a source of ions necessary for pinching. (Shots with a small radius cathode at the diode--2.5 cm and 5 cm diam--and no PFD also show pinching although it is not as intense.)
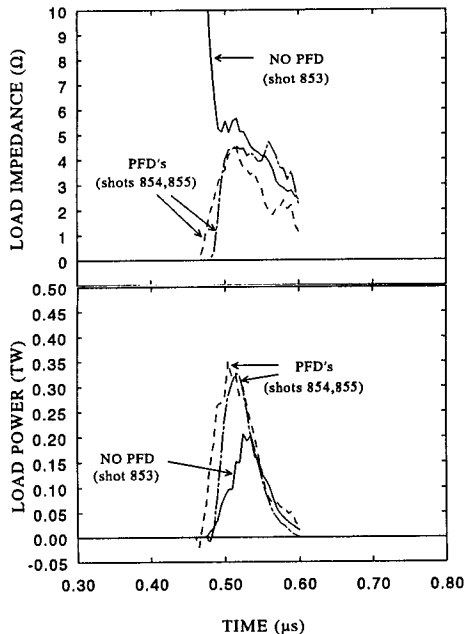

Fig. 7 Load power on PFD shots is up to 1.7 times higher than vacuum diode shots for short POS conduction times and the same load impedance at peak power.

The control of load impedance provided by the PFD is illustrated in Fig. 8. This figure shows two PFD shots with the same POS conduction time and large diode gap, but different PFD delays. Peak load power is the same on these two shots--just over 0.5 TW. In the upper graph, the PFD delay is short and opening is switch-limited: the load impedance at peak power (~4 Ω) and the voltage generated are high, current transfer is fairly low. In contrast, in the bottom graph the PFD delay is long and performance is load-limited: the impedance at peak power (~2 Ω) and the voltage generated are limited, while the current transfer efficiency is good.
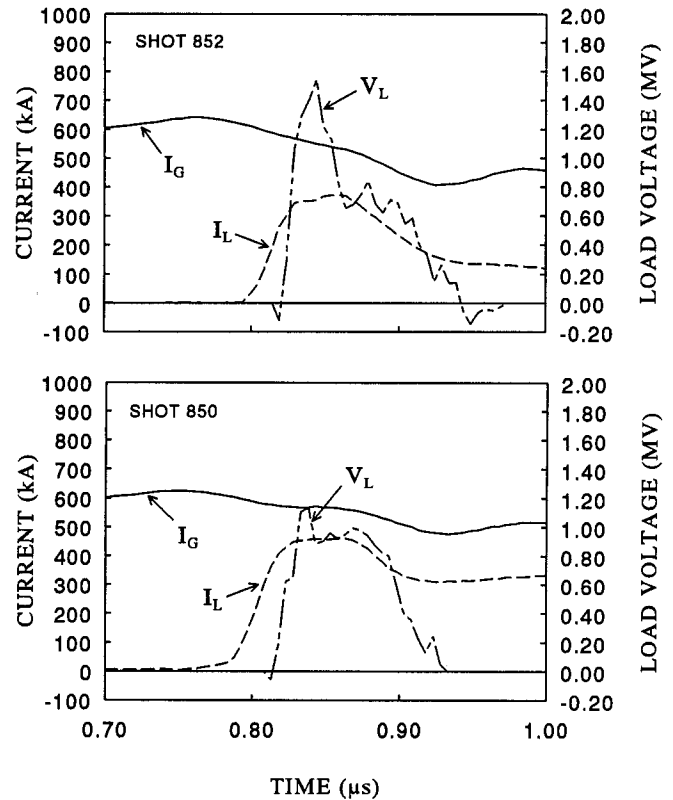

TIME (μs)

Fig. 8. Control of load impedance at peak power and thus load voltage and current is possible with an independent PFD. With a) short PFD delays performance is switch-limited; with b) long PFD delays performance can be load-limited.

Helical Center Conductor

A helical cathode center conductor with a pitch of four and a nominal 10 cm diam was used in the switch region. The helix is 20 cm long and has four slots. Each rib makes ~2.5 turns around the helix. It was not centered under the flashboards/anode rods, but displaced about 4 cm downstream. This was done so that the center-of-mass of the plasma, which may translate downstream about half the switch length or 4 cm during conduction, is at the center of the helix (where the field is highest) at opening. The additional axial field increases the total insulating magnetic field in the central region of the helix a factor of 2.3 above that from a solid cathode of the same diameter.

Switch opening with the helix was generally very poor, although there appeared to be different "regimes" of operation. Conduction times for a particular plasma delay were typical of solid 10 cm diam cathodes. For long delays of ≥1 μs the switch conducts for ~1μs, but with small load currents and low voltage generated upon opening with

both short circuit and diode loads. Most of the current stays in the switch. With intermediate delays, from 0.5 to 1 μs, the switch did not open at all for both short circuit and diode loads. For short delays, less than 0.5 μs, the switch conducts for 350 ns and less. With short circuit loads switch opening was much improved and all the current reached the load. (No data was taken with diode loads at these short conduction times.) Current appeared to be flowing in the helix ribs on the short plasma delay shots, because the ribs were deformed by magnetic forces during the pulse. This did not occur with the longer plasma delays and suggests that in this case current is carried in the plasma, not the helix, for most of the pulse. The fact that switch opening here is inferior to the solid cathode suggests that it is not simply a matter of the helical turns shorting out. Also, the B_z field decreases to zero at the ends of the helix and this may result in additional electron losses downstream of the switch. To retrap some of this flow, the cathode just downstream of the helix was reduced to 5 cm diameter on some shots, resulting in a slight improvement in performance.

Gas Gun Plasma Sources

Four gas guns, similar to those in ref. 4, were used as an opening switch plasma source with H_2, He, and Ar gases. The gas, at 60 psig back pressure, was fed into the region between the coaxial electrodes, where the plasma discharge is initiated, through an automobile fuel injector used as the mechanical valve[5]. Typically, the valve is pulsed at least several hundred microseconds before the discharge is initiated in the gun by a capacitor bank. This minimum gas puff delay is needed to initiate the gun discharge and involves the time it takes for the valve to start opening and the transit time of the gas from the valve to the location near the front of the gun where gas breakdown occurs. Best performance with H_2 and He gases occurred with gas puff delays of 400 to 450 μs. For Ar, gas puff delays of ~500 μs resulted in best performance, consistent with its slower thermal velocity. The plasma produced by the guns typically has a slower velocity and is more localized than flashboard plasma.

Tapered cathodes, as well as 10 cm diam and 2.5 cm diam straight cathodes, were used with the gas guns. The gun to cathode distance was varied from 3.5 to 10 cm. Two B-dot current monitors, ILU2 and ILL2 which are located behind the diode, were used on these gas gun shots in addition to the standard load current monitors, ILU and ILL, which are 5 cm upstream of the diode. In typical operation, these two sets of current monitors agree: little current is lost over the 5 cm distance from the standard current monitors to the load. Even in switch-limited operation, most of the current loss, which can be a substantial fraction of the total current, occurs near the load but upstream of the standard load current monitors ILU and ILL.

Switch performance with a 10 cm diam cathode was equivalent for the different gases (but at different gas puff, plasma delays). In addition, performance is very similar to flashboards: voltage and load power improve with conduction time and at 900 ns conduction the switch voltage is ~800 kV. Figure 9 shows the peak switch voltage as a function of load impedance at peak power for shots with He gas. On the longest conduction shots, the voltage is 800 kV at load impedances of ~2 Ω and above (similar to flashboards). Highest load power, about 0.4 TW, occurs at this 2 Ω critical impedance, also comparable to flashboards.

Performance with a 2.5 cm diam cathode was, again, independent of the gas used. Voltage and load power improve with conduction time up to 600 ns, similar to flashboards. In Fig. 10, the peak switch voltage is plotted versus load impedance at peak power for shots with H_2 gas. For these shots, switch-limited operation may not have been reached and voltages higher than 1.3 MV may be possible if the load impedance is increased above 5.5 Ω.

For the 10 to 2.5 cm diam tapered cathode (tapering in switch) the voltage is 1.4 MV at the ~4 Ω critical impedance and above (Fig. 11 with H_2 gas). This is also similar to flashboards with tapered cathodes. However, in what is atypical behavior, the switch-limited voltage does not increase with conduction current, but is constant at 1.4 MV over a range of conduction currents from 350 to 550 kA.
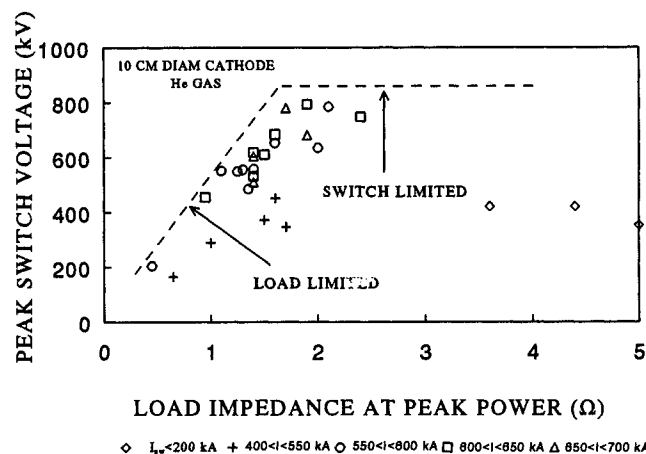

Fig. 9. Peak voltage as a function of load impedance at peak power with a 10 cm diam cathode and gas gun plasma sources (He gas here).
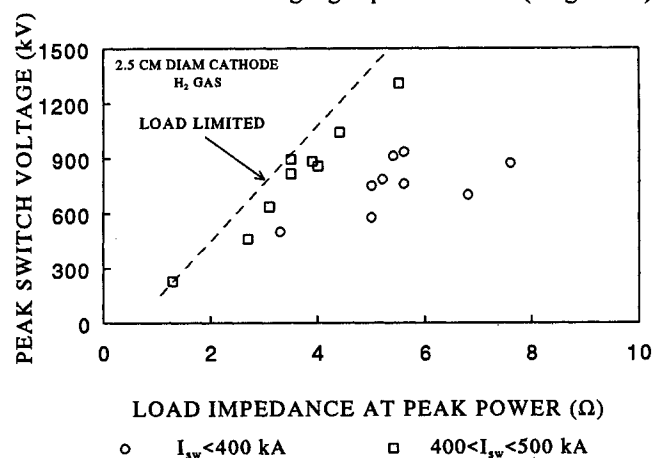

Fig. 10. Peak voltage as a function of load impedance at peak power with a 2.5 cm diam cathode and H_2 gas.
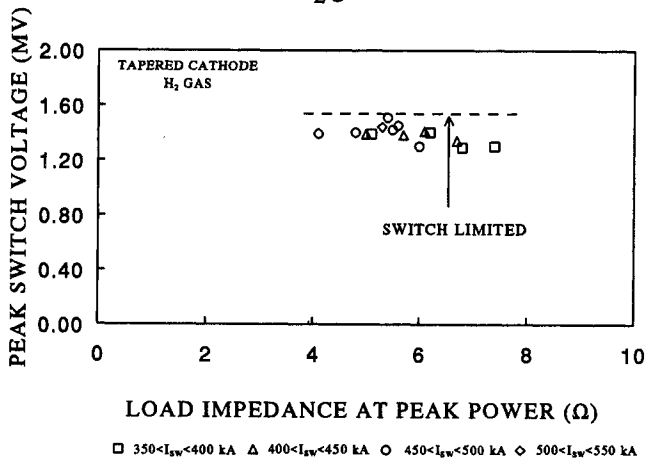

Fig. 11. Peak voltage as a function of load impedance at peak power with a tapered cathode and H_2 gas.

Summary

Recent experiments on Hawk illustrate the importance of the electrode geometry on switch performance. Cathode and anode

configurations have an impact on switch opening. Tapering the cathode over the 8 cm POS length from 10 cm diam to a 2.5 cm diam is a good compromise between the high voltage generated with a small radius cathode and the longer conduction/higher currents associated with the larger cathodes, producing load powers of 0.7 TW (1.6 MV, 450 kA) with 55 kJ--20% energy efficiency--delivered to the diode. There is a limit on the minimum radial gaps in the switch and downstream of the switch below which voltage and current transfer efficiency are reduced. For example, switch opening with a straight 10 cm diam cathode deteriorated when the radial gap downstream of the switch was reduced to that used in the switch.

The load power was up to 70% higher with a PFD used in conjunction with the POS for short conduction times (400 ns and less), where switch plasma does not reach the load. On longer conduction time shots, the effect was less pronounced, with about a 30% enhancement with the PFD. In this case, however, some switch plasma reached the load so there were no true vacuum diode shots for comparison.

A helical center conductor in the switch region, designed to increase the total insulating magnetic field for a given cathode radius, resulted in dramatically degraded switch opening (low voltage, poor current transfer) for >350 ns conduction times with both short circuit and diode loads. Opening was good for <350 ns conduction with short circuit loads. Indications were that current was carried in the helix only on the short conduction time (low plasma density) shots, because the helical ribs were deformed by magnetic forces on these shots.

Switch/load performance with gas guns was generally comparable to that with flashboards in a given switch/load configuration. Performance was independent of the gas (H$_2$, He, and Ar) used.

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